Galaxies and Cosmology

Jörn Wilms, Matthias Kadler

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Dr. Karl Remeis-Sternwarte, Bamberg & ECAP
`joern.wilms@sternwarte.uni-erlangen.de`
`matthias.kadler@sternwarte.uni-erlangen.de`
Tel.: (0951) 95222-13/26

`pulsar.sternwarte.uni-erlangen.de/wilms/teach/galcos_ws09`

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Friedrich–Alexander–Universität Erlangen–Nürnberg

Introduction

Contents: Galaxies

Introduction		
19 Oct	JW	Organization; Stars and Galaxy
20 Oct	JW	Galaxies, Evolution of the Universe
Local Group		
26 Oct	JW	Members, Motions
02 Nov	JW	Chemical Evolution, Dwarf Galaxies
Spiral Galaxies		
03 Nov	JW	Global Properties, Distribution of Gas
09 Nov	JW	Barred Spirals, Density Wave Theory
16 Nov	MK	Bulges and Centers
Elliptical Galaxies		
17 Nov	MK	Global Properties, Distribution of MAtter
Galaxy Clusters		
23 Nov	MK	Galaxy Statistics, Interactions, Starbursts
Active Galactic Nuclei		
30 Nov	MK	Seyfert Galaxies, Radio Loud Galaxies, Unified Model
01 Dec	MK	Galaxy Centers: Accretion and Black Hole Paradigm

Contents: Cosmology

Classical Cosmology		
07 Dec	MK	Introduction, FRW
14 Dec	MK	Distance Scale, H_0
The Early Universe		
21 Dec	JW	Hot Big Bang, Nucleosynthesis
22 Dec	JW	Inflation
Properties of the Universe		
11 Jan	JW	Measurement of Ω
12 Jan	MK	Measurement of Λ
Structure Formation		
18 Jan	JW	Measurement of Structure
25 Jan	JW	Theoretical Structure Formation
01 Feb	JW	Cosmic Microwave Background
02 Feb		EXAM
08 Feb	JW	Measurement of w
09 Feb	JW	Cosmology with Galaxy Clusters: eROSITA

Textbooks

Sparke & Gallagher, 2007, *Galaxies in the Universe – an Introduction*, Cambridge: CUP, 40.99 € (softcover)

Textbook for the 1st half of the class, somewhat lower level than what we will be teaching, but a very good overview nevertheless.

Binney & Merrifield, 1998, *Galactic Astronomy*, Princeton: Princeton University Press, 55 €, 791 pp.

Advanced level book on Galactic astronomy, the standard for graduate level courses, so higher than what we will be doing, but a very good book if you want to continue to do astronomy. Recommended.

Schneider, P., 2005, *Einführung in die Extragalaktische Astronomie und Kosmologie*, Heidelberg: Springer, 59.95 € (available as an e-book)

Well written introduction to cosmology, approximately at the level of this lecture. Recommended.

Textbooks

Peacock, J.A., 1999, *Cosmological Physics*, Cambridge: Cambridge Univ. Press, 49.50 €

Very exhaustive, but difficult to read since the entropy per page is *very* high. . . still: a “must buy”.

Longair, M.S., 1998, *Galaxy Formation*, Berlin: Springer, 53.45 €

Clear and pedagogical treatment of structure formation.

Carroll & Ostlie, 2007, *Modern Astrophysics*, Reading: Addison-Wesley, 80 €(softcover), 1400 pp.

Advanced level, expects good physics background, generally I like their stellar astrophysics part better than their extragalactic one.

Exercises and Exam

We will have 2 h long exercise sessions led by Thomas Dauser and Victoria Grinberg approximately every 2 weeks at the following dates:

27 Oct	Milky Way
10 Nov	Spiral Galaxies
24 Nov	ADS, NED, Simbad, Proposals
08 Dec	World Models
15 Dec	1st Iteration Proposals
19 Jan	Observing Panel
26 Jan	1 h Test Exam
02 Feb	EXAM

Note that your presence at the exercise sessions is mandatory

(unless you have a lab experiment)

In general, exercises are “in class” (i.e., no homeworks).

We will also give out reading assignments and other exercises to help you with the course.

Exercises and Exam

In addition to standard practicals, we will go through an “observing proposal” exercise, where you will

. . . write (alone or with a partner) an one page scientific justification for an astronomical observation

. . . discuss a preliminary draft with one of us

. . . read ∼five proposals written by your colleagues and present them in an “observing panel”

. . . rank proposals by scientific importance.

Overview

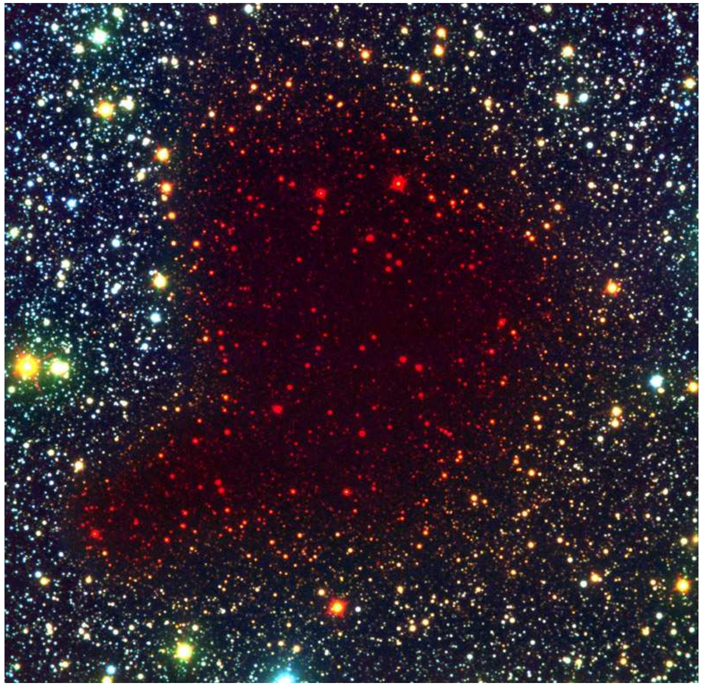
Introduction

Galaxies and the universe consist of stars, and basic knowledge on the properties of stars and of Galaxies is required.

Before starting with this course, we will therefore briefly review the most important properties of stars, the Milky Way, Galaxies and the Universe, to bring everybody up to speed.

For details please consult lecture notes for “Introduction to Astronomy” at `http://pulsar.sternwarte.uni-erlangen.de/wilms/teach/intro`

Optical View of B68 (ESO; VLT/FORS1)



IR View of B68 (ESO; VLT/FORS1 + NTT/SOFI)

Formation

Stars are born in “Giant Molecular Clouds”

Typical GMC parameters (e.g., Orion):

- large clouds: typical diameters 50–100 pc
- contain lots of molecular gas (H_2, CO, alcohol,…).
- typical temperatures: 10–20 K (coolest regions in the interstellar medium)
- typical particle densities $n \sim 10^6$–$10^{10}\,\mathrm{cm}^{-3}$

Stars are born in groups out of collapsing Molecular Clouds.

Collapse triggered, e.g., by collisions of clouds or shocks caused by nearby supernovae.

Formation

Criterion for collapse: Cloud is instable, i.e., gravitation is stronger than thermal pressure.

In terms of thermal and gravitational energies, this means

$$\frac{3}{2}\frac{M}{m_\mathrm{p}}kT - \frac{3}{5}\frac{GM^2}{R} \le 0 \tag{2.1}$$

which can be expressed as

$$\frac{M}{R} \ge \frac{5}{2}\frac{kT}{Gm_\mathrm{p}} \quad \text{or} \quad \frac{4\pi}{3}\rho R^2 \ge \frac{5}{2}\frac{kT}{Gm_\mathrm{p}} \tag{2.2}$$

$\Longrightarrow$ Depends on R, collapse thus possible for

$$R > R_\mathrm{J} = \sqrt{\frac{15kT}{8\pi G m_\mathrm{p}\rho}} \sim \sqrt{\frac{kT}{Gm_\mathrm{p}\rho}} \tag{2.3}$$

where R_J is called the Jeans radius.

Formation

Plugging in typical typical numbers, i.e., $T \sim 50\,\mathrm{K}$, particle density $n = 10^5$ H-atoms cm^{-3} (=a mass density of $\rho = nm_\mathrm{p} \sim 1.7 \times 10^{-9}\,\mathrm{g\,cm^{-3}}$) gives $R_\mathrm{J} \sim 0.2\,\mathrm{pc}$.

For a given Jeans radius, the mass within R_J is the Jeans mass

$$M_\mathrm{J} \sim \frac{4\pi}{3}R_\mathrm{J}^3\rho \tag{2.4}$$

…which has typical values of 50–100 $M_\odot$, i.e., larger than one star!

In reality things are more complicated: ISM contains magnetic fields

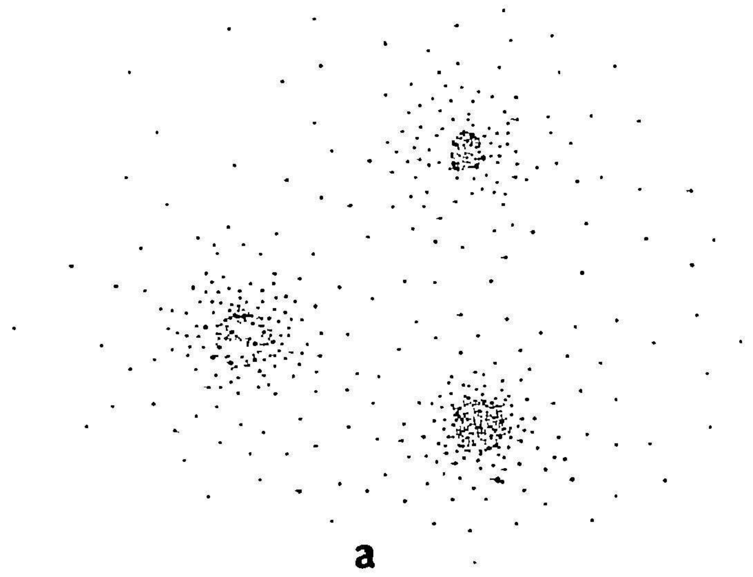
$\Longrightarrow$ Particle motion $\perp$ B-field lines difficult

$\Longrightarrow$ stops gas from collapsing.

This is good since Jeans formalism alone predicts too strong star formation.

$\Longrightarrow$ Need star formation with magnetic fields

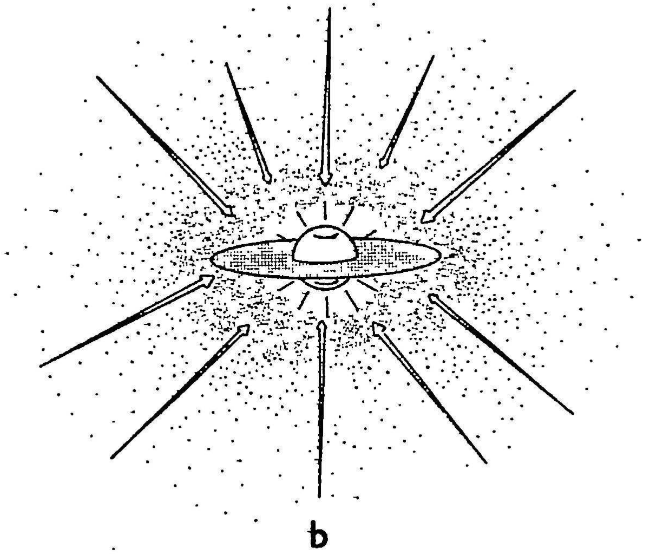
See Shu et al. (1987, Annual Reviews of Astronomy and Astrophysics 25, 23) for the gory details.



Shu et al. (1987, ARAA 25, 23, Fig. 7)

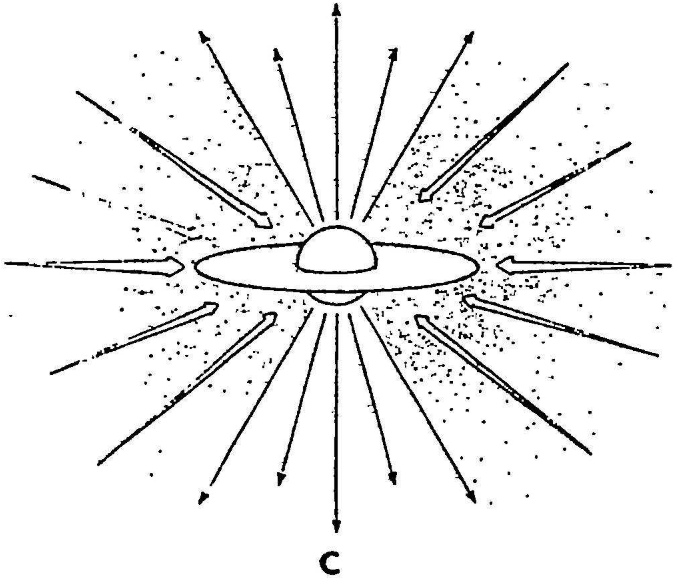
Stellar mass cores form from fragmentation of larger pieces.

Note: fragmentation only along B-field lines.



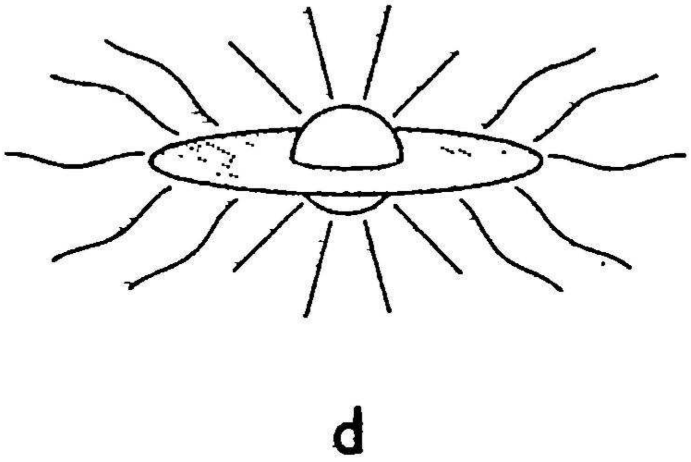
Shu et al. (1987, ARAA 25, 23, Fig. 7)

Protostar forms with surrounding disk ("inside out collapse") once core hot enough to allow fusion ($T > 10^6$ K)



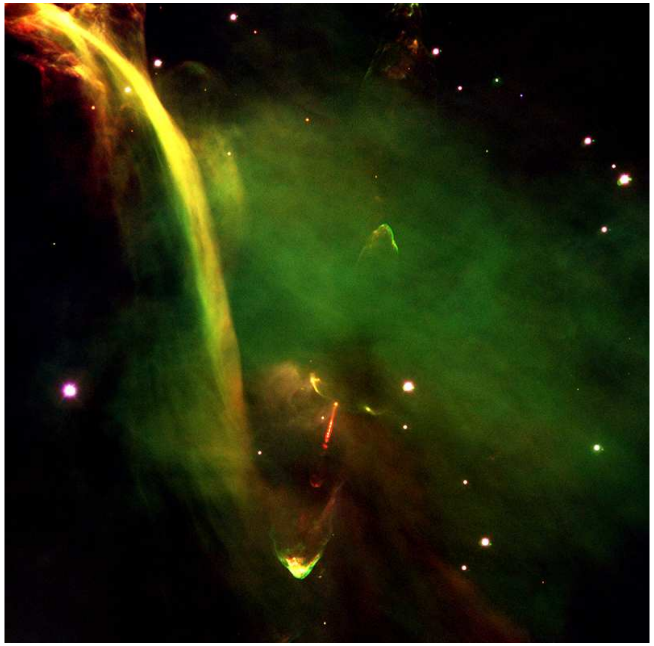
Shu et al. (1987, ARAA 25, 23, Fig. 7)

Stellar wind forms bipolar outflow



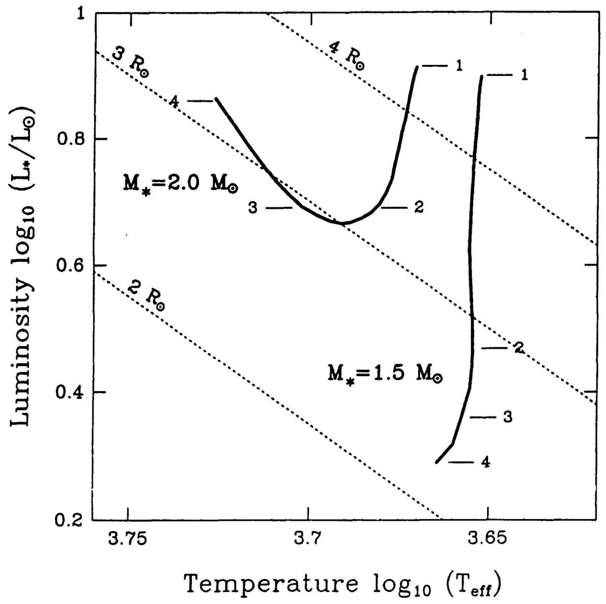
Shu et al. (1987, ARAA 25, 23, Fig. 7)

Star has reached zero age main sequence (ZAMS) plus circumstellar disk.
Some disks produce fast collimated outflows (jets): Herbig Haro Objects



HH34 in Orion (ESO VLT KUEYEN/FORS2)

Herbig Haro Objects: shocks and jets/outflows produced during formation of stars.



Palla & Stahler (1993, ApJ 418, 414; numbers are time in 10^6 years)

Stellar Evolution from protostar to ZAMS takes a few million years.

Zero Age Main Sequence

Once star has collapsed and nuclear fusion has started: zero age main sequence (ZAMS) is reached

The Main Sequence is the result of steady state fusion (“burning”) of hydrogen into helium in stellar centers.

. . . longest phase of stellar evolution (10 billion years for Sun)

Stellar structure defined by balance between pressure inwards due to gravitation and pressure outwards due to energy release (“hydrostatic equilibrium”).

Zero Age Main Sequence

The structure of stars is defined by a set of four coupled differential equations which express the basic conservation and transport quantities always encountered in physics:

1. Mass conservation
2. Momentum conservation (=hydrostatic equilibrium)
3. Energy conservation
4. Energy transport

and quantities expressing the physical properties of material, mainly:

1. Energy generation
2. Equation of state (=dependence of density of material from physical conditions)

Zero Age Main Sequence

Stellar structure governed by four coupled differential equations:

Mass structure
(mass conservation)

$$\frac{\mathrm{d}M}{\mathrm{d}r} = 4\pi r^2 \rho(r)$$

Pressure structure
(hydrostatic equilibrium)

$$\frac{\mathrm{d}P}{\mathrm{d}r} = -\rho(r)\frac{GM(r)}{r^2}$$

Temperature structure
(e.g. radiative transfer)

$$\frac{\mathrm{d}T}{\mathrm{d}r} = -\frac{3}{4ac}\frac{\kappa\rho(r)}{T^3}\frac{L(r)}{4\pi r^2}$$

Energy conservation

$$\frac{\mathrm{d}L}{\mathrm{d}r} = 4\pi r^2 \rho(r)\epsilon(r)$$

plus “equation of state” ($P = P(T, \rho)$), Opacities $\kappa(T, \rho, Z)$ = interaction of radiation with gas, energy generation ($\epsilon = \epsilon(T, \rho, Z)$),. . .

Stellar model: numerical solution of stellar structure equations.

Energy generation: Overview

Main sequence: Nuclear fusion of Hydrogen into Helium:

$$4\text{p} \longrightarrow {}^4_2\text{He} + E$$

How much energy is gained?

Particle physics: express mass as “rest energy equivalent” via $E = mc^2$

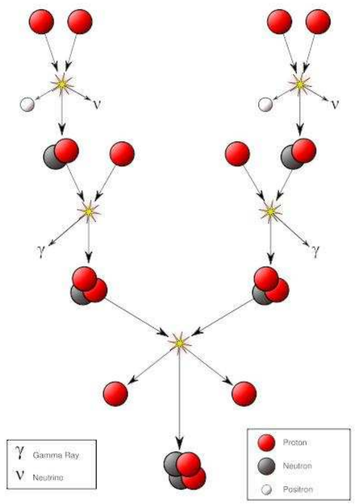
(and call it “mass”. . .); usually use energy units of MeV, 1 MeV $= 1.602 \times 10^{-13}$ J

	mass of 4 protons (4 × 938 MeV):	3752 MeV
−	mass of ${}^4_2$He:	3727 MeV
	mass defect Δmc^2:	25 MeV

In the fusion of hydrogen to helium, 0.7% of the available rest mass energy is converted to energy.

Two main burning cycles: proton-proton chain and the CNO cycle.

Energy generation: Proton-Proton chain



For moderate central temperatures, He is produced using the proton proton chain.

First, two protons create a deuteron:

$$^1\text{H} + {}^1\text{H} \longrightarrow {}^2\text{H} + \text{e}^+ + \nu_\text{e} \tag{2.5}$$

This process is slow (happens once for a nucleon per 10^{10} years)

Then an additional proton is attached:

$$^2\text{H} + {}^1\text{H} \longrightarrow {}^3\text{He} + \gamma \tag{2.6}$$

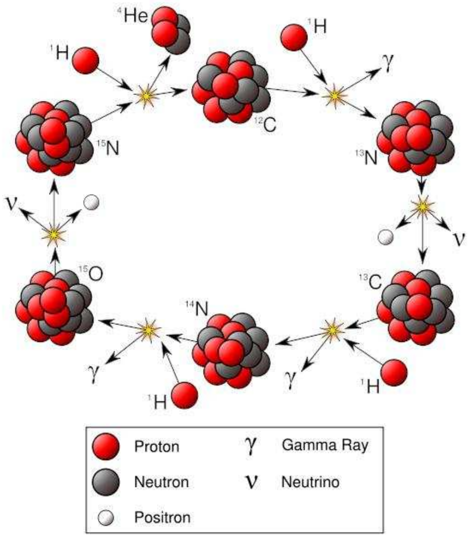
and two helium nuclei can form an alpha particle:

$$^3\text{He} + {}^3\text{He} \longrightarrow {}^4\text{He} + 2{}^1\text{H} \tag{2.7}$$

This is the so called pp I-cycle, minor variations of the theme exist (pp II, pp III cycles), but pp I dominates.

pp chain dominates for $T \lesssim 2 \times 10^7$ K, $\epsilon_\text{pp} \propto T^5$; Sun: 98.4%.

Energy generation: CNO cycle



The CNO cycle (Bethe-Weizsäcker-cycle) requires the presence of C, N, and O isotopes as catalysts.

CNO cycle has slightly smaller energy release than pp-cycle because of higher neutrino losses.

Reaction ^{14}N + p $\longrightarrow$ ^{15}O + γ is th slowest reaction (one million years).

CNO cycle dominates above 2×10^7 K, $\epsilon_\text{CNO} \propto T^{17}$; Sun: 1.6%.

Wikipedia

Characteristic Timescales

Main sequence: Hydrogen burning at the center.

Evolution timescale dominated by the nuclear timescale = timescale needed to use the fuel in the center of the star.

According to simulations, this is ∼10% of the available Hydrogen.

Since 0.7% of $M_\text{core}c^2$ converted into He, the nuclear timescale is

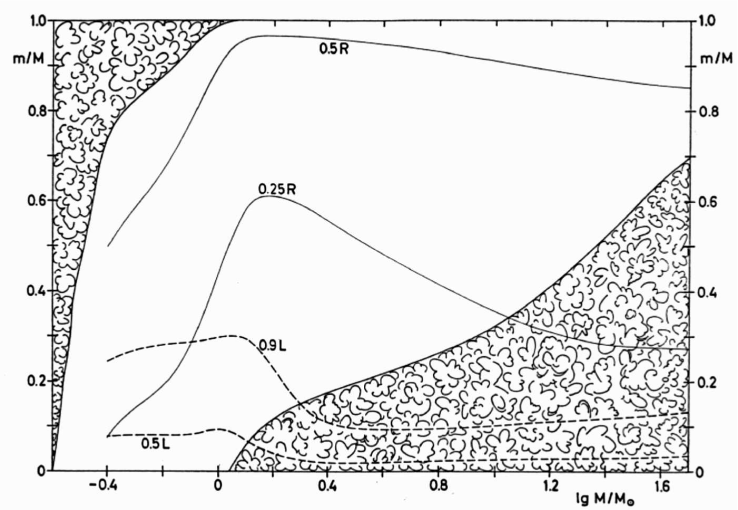
$$t_\text{n} = \frac{0.007 \cdot 0.1Mc^2}{L} = \frac{M/M_\odot}{L/L_\odot} \cdot 10^{10}\,\text{years} \tag{2.8}$$

A second important timescale is the timescale the star would need to radiate its stored thermal energy: thermal timescale.

Roughly given as

$$t_\text{t} = \frac{0.5GM^2/R}{L} = \frac{(M/M_\odot)^2}{(R/R_\odot)(L/L_\odot)} \cdot 2 \times 10^7\,\text{years} \tag{2.9}$$

Internal Structure



Kippenhahn diagram: Internal Structure of Main Sequence stars

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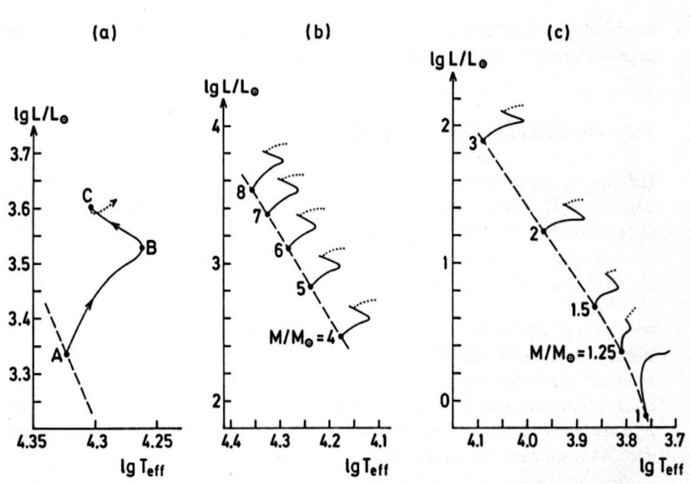
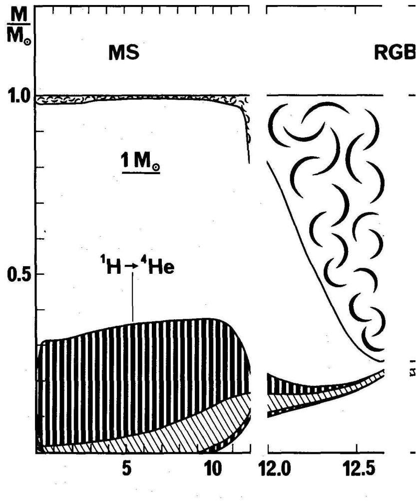
Evolution on the Main Sequence



main sequence evolution from zero age to helium exhaustion

Evolution: Low Mass Stars

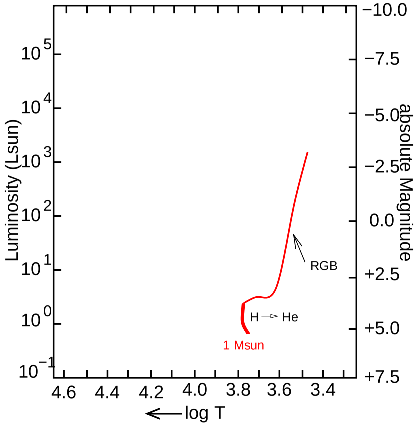


(Maeder & Meynet, 1989)

Once H is exhausted in center: H continues to burn in a shell around the He core (“shell burning”).

For stars with $M \lesssim 1\,M_\odot$: Star reacts by expanding convective hull until it is almost fully convective.

Evolution: Low Mass Stars



(after Iben, 1991)

Once H is exhausted in center: H continues to burn in a shell around the He core (“shell burning”).

For stars with $M \lesssim 1\,M_\odot$: Star reacts by expanding convective hull until it is almost fully convective.

$\Longrightarrow$ luminosity increases, temperature decreases

$\Longrightarrow$ motion in HRD horizontally towards the right, then upwards to higher L: red giant stage.

Evolution: Low Mass Stars

After H-burning, note that stars are in hydrostatic equilibrium: inwards gravitational pressure balanced by outwards gas pressure

Note: gas pressure, emphnot radiation pressure!

Since the gas pressure is $P \;=\; nkT$: energy source needed to heat gas (=fusion).

This is a problem for the core during the red giant stage, as virtually no fusion ongoing

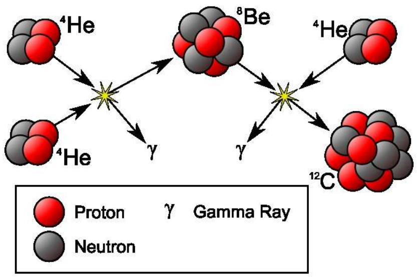
$\Longrightarrow$ Core gets compressed

$\Longrightarrow$ ρ and T increase

BUT: collapse cannot continue indefinitely!

$\Longrightarrow$ once ρ has increased appreciably, there must be a point where the Pauli principle becomes important: stellar matter degenerates, resulting in $P \propto \rho^{5/3}$ (independent of T!)

Evolution: Low Mass Stars



In the degenerate core, once $T_{\text{core}} \sim 100 \times 10^6$ K: Triple alpha process starts:

$$^{4}\text{He} + {}^{4}\text{He} \leftrightarrow {}^{8}\text{Be}$$
$$^{8}\text{Be} + {}^{4}\text{He} \rightarrow {}^{12}\text{C}$$

Since ^{8}Be has a half life of only 2.6×10^{-16} s: this can only work effectively if 3 α-particles collide.

But core is degenerate:

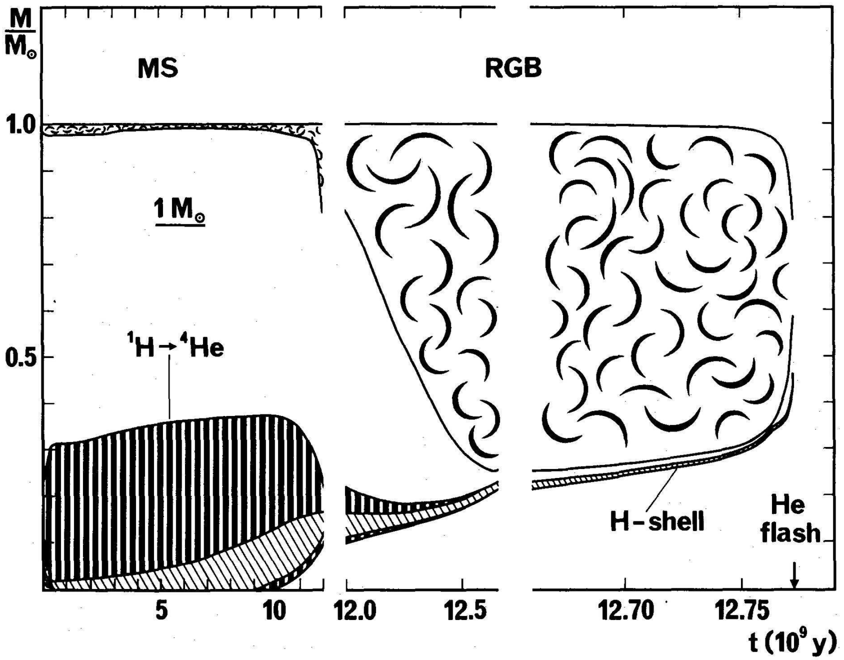
$\Longrightarrow$ High thermal conductivity of electrons

$\Longrightarrow$ core has uniform temperature

$\Longrightarrow$ 3α onset is rapid

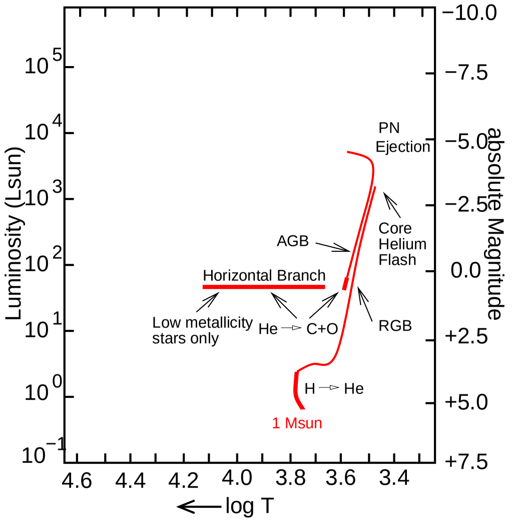
$\Longrightarrow$ He flash

Not seen on surface ("buffered" by convective envelope).



Evolution of the structure of a 1 $M_\odot$ star to the Helium flash (Maeder & Meynet, 1989).

Evolution: Low Mass Stars



After the He flash, He burning in core and H shell burning

$\Longrightarrow$ expansion starts again

$\Longrightarrow$ "asymptotic giant branch"

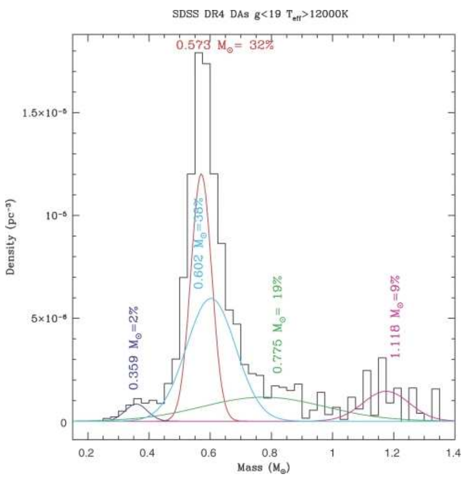
Unstable He fusion processes ("thermal pulses") lead to ejection of outer layers (∼50% of total mass!)

Effect of He core being unable to transport energy away quickly enough.

$\Longrightarrow$ inner (hotter) parts of star become visible.

after Iben (1991)

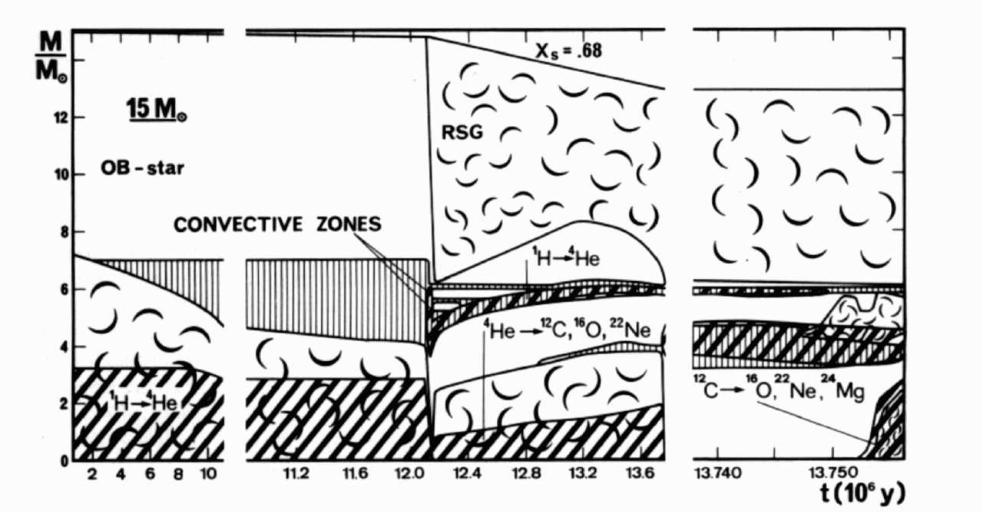
Evolution: Low Mass Stars



mass distribution of 1733 white dwarfs
(Kepler et al. 2007, MNRAS 375, 1315)

White Dwarfs

1. End stages of evolution of stars born with $M \lesssim 8\,M_\odot$
2. mainly consist of C and O
3. Radius $\sim$ Earth
4. typical density $\rho \sim 10^6\,\mathrm{g\,cm^{-3}}$
5. typically $M \sim 0.6 M_\odot$
   $M < 1.44\,M_\odot$ (Chandrasekhar mass); above that: relativistic degenerate gas ($P \propto \rho^{4/3}$), can show that under these circumstances WD is not stable.



Evolution of the internal structure of a 15 $M_\odot$ star.

Massive Stars

Massive stars: Evolution on MS similar but faster than for low mass stars.

More massive stars reach threshold temperature for 3α and subsequent nuclear burning before reaching degeneracy

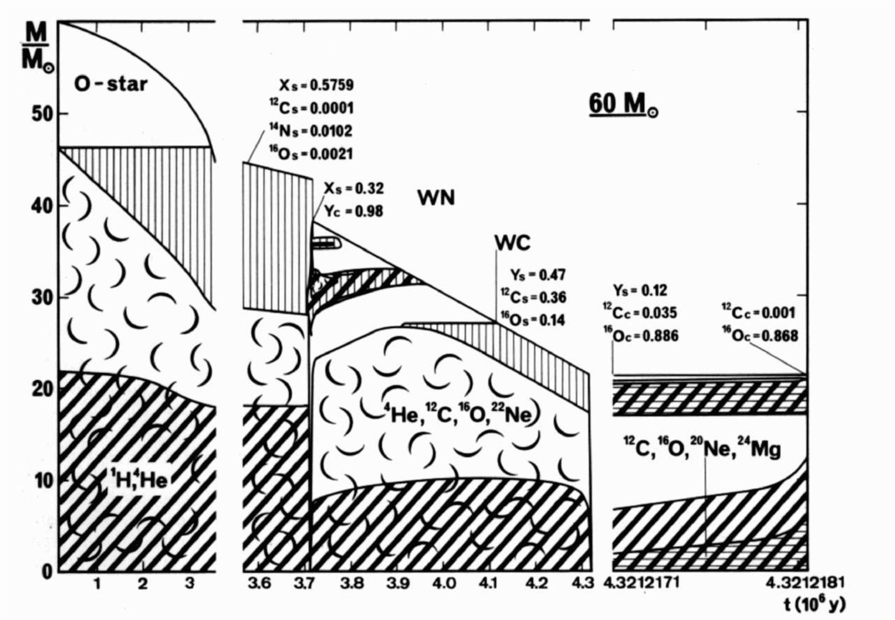
$\Longrightarrow$ He just starts to burn.

In these objects, higher order fusion processes can kick in (but are energetically unimportant): alpha reactions

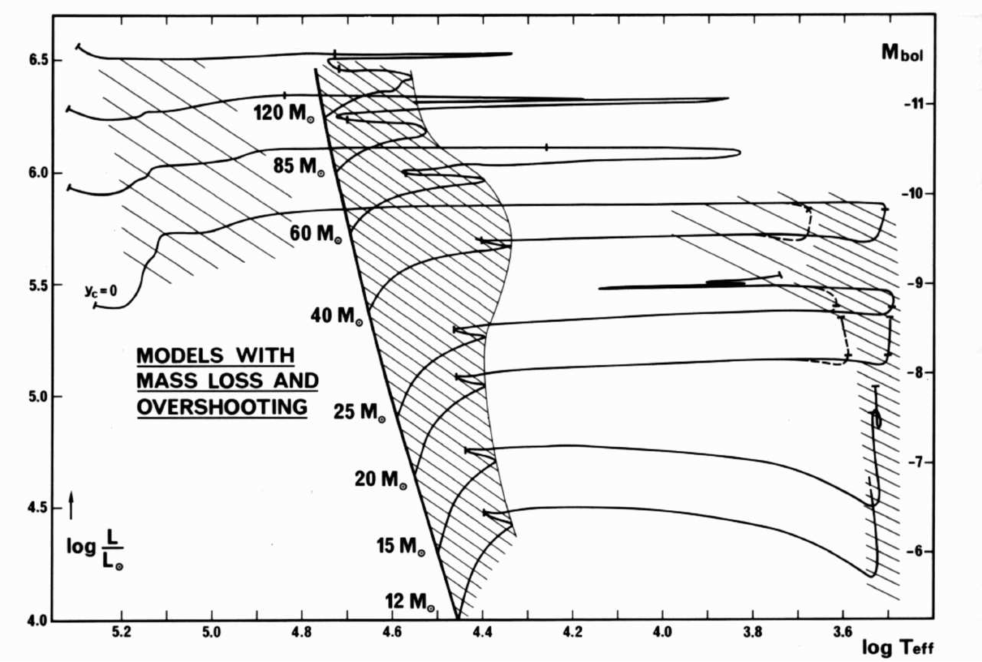
$$\begin{aligned}
{}^{12}\mathrm{C} + {}^{4}\mathrm{He} &\rightarrow {}^{16}\mathrm{O} + \gamma \\
{}^{16}\mathrm{O} + {}^{4}\mathrm{He} &\rightarrow {}^{20}\mathrm{Ne} + \gamma \\
{}^{20}\mathrm{Ne} + {}^{4}\mathrm{He} &\rightarrow {}^{24}\mathrm{Mg} + \gamma
\end{aligned}$$

Outer layers continue H shell burning.

During evolution of star on red giant branch: convective hull moves deeper into core, can mix fusion products into outer layers.

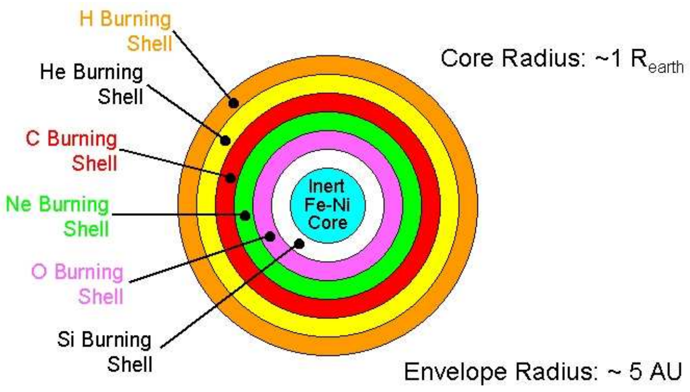


Evolution of the internal structure of a 60 $M_\odot$ star.
Note the very strong mass loss!



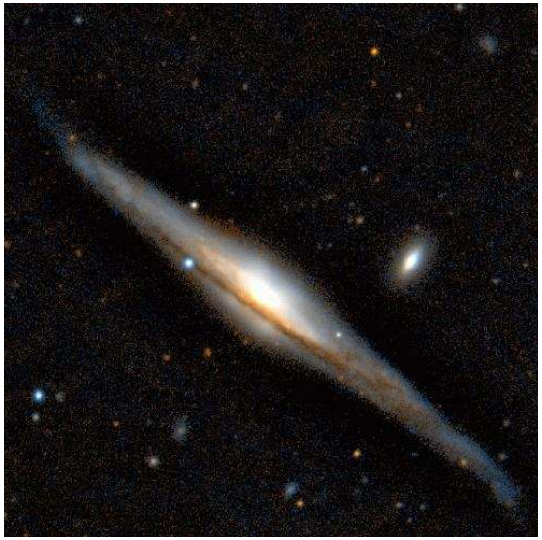
Summary: Evolution of massive stars in the HRD.

Massive Stars



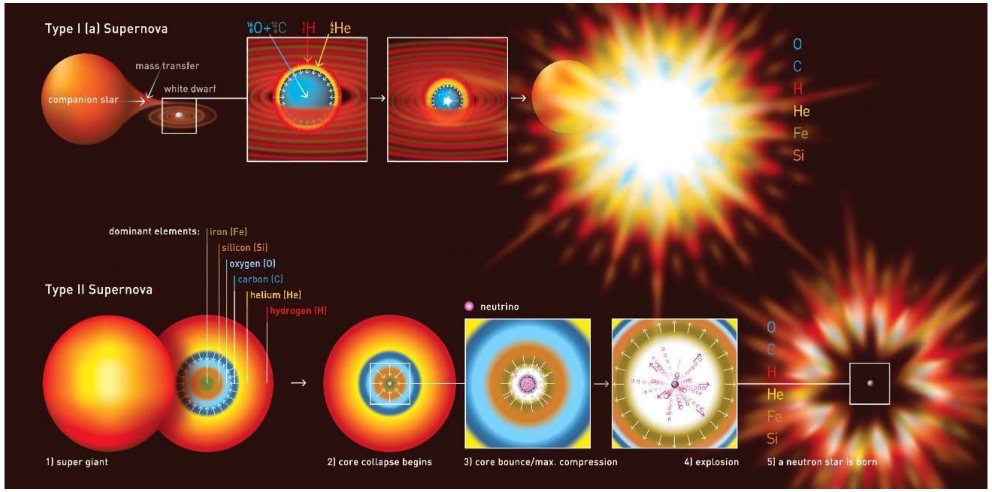
successive stages of nuclear burning: final state: onion-shell model

1. H burning, ash: He
2. He burning, ashes: C, O, Ne, Mg
3. C burning, ashes: Ne, Na, Mg
4. Ne burning, ashes: O, Mg . . .
5. O burning, ashes: Si, P, S, . . .
6. Si burning, ashes: Fe, Ni



Type II SN2001cm in NGC5965 (2.56 m NOT, Håkon Dahle; NORDITA)

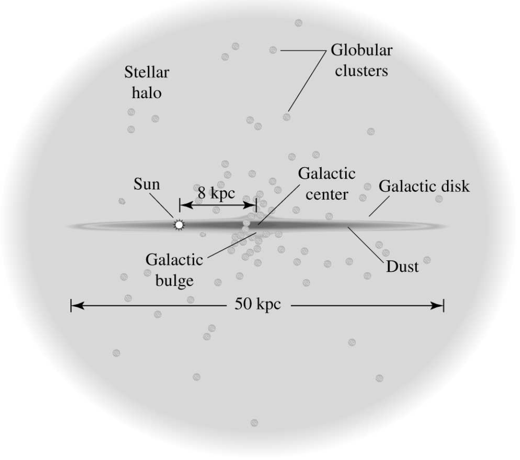
Evolution of more massive stars: fusion up to ^{56}Fe, then no energy gain $\Longrightarrow$ no pressure balance in centre $\Longrightarrow$ supernova explosion of type II. *energy release:* 10^{46} W ($10^{20} L_\odot$; about 1% in light, rest in neutrinos)



F.K. Thielemann

Outcome: Neutron Stars or Black Holes

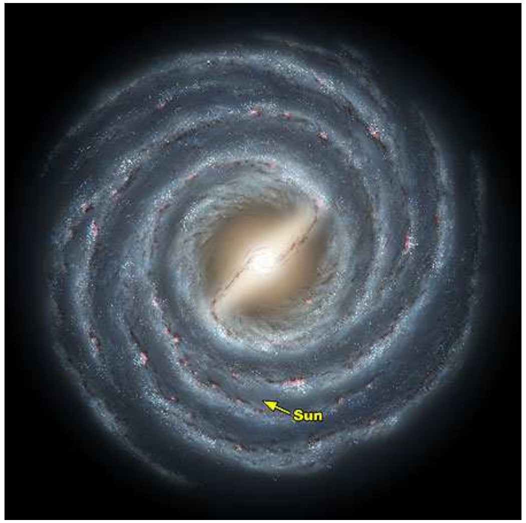
Structure of the Galaxy



components of the Milky Way:

- Galactic disk:
  - rotating
  - young & old stars, open star clusters
  - gas & dust
- Galactic halo:
  - non-rotating,
  - old stars only, globular clusters
  - no gas, no dust
- Galactic bulge: rigid rotation

Structure of the Galaxy



Milkyway is a barred spiral galaxy Luminosity:
$\sim 2\times 10^{10}\,L_\odot$
Mass: $\sim 10^{11}\,M_\odot$ (radiating)
$\sim 10^{12}\,M_\odot$ (total)
Stellar density: $\sim 0.3\,M_\odot\,\mathrm{pc}^{-3}$

$1\,M_\odot = 2\times 10^{33}\,\mathrm{g} = 2\times 10^{30}\,\mathrm{kg}$,
$1\,L_\odot = 4\times 10^{33}\,\mathrm{erg\,s^{-1}} = 4\times 10^{26}\,\mathrm{W}$

Evidence for Spiral Arms

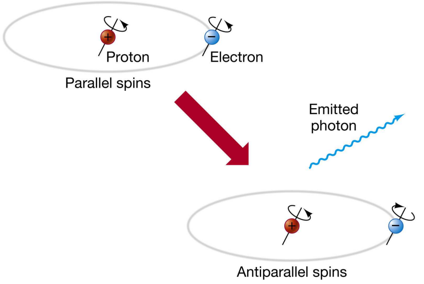
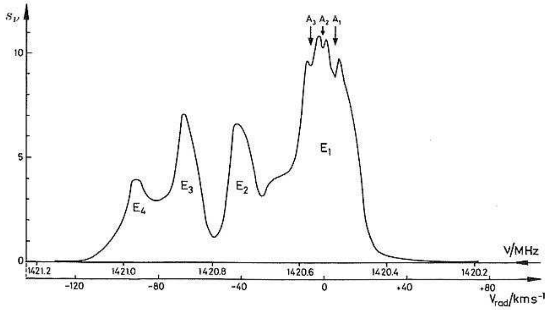


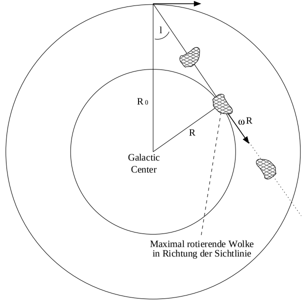
Image: 2005, Pearson Prentice Hall, Inc.

- Spins of electron and proton may be parallel ($F = 1$) or antiparallel ($F = 0$) (“hyperfine levels”); energy difference of $\Delta E \sim 6\times 10^{-6}\,\mathrm{eV}$, corresponding to $\lambda = 21\,\mathrm{cm}$ or $\nu = 1.4\,\mathrm{GHz}$.
- $F = 1$ is metastable, i.e., long life time (10^7 years); transition to $F = 0$ *dipole forbidden* in quantum mechanics, transition rate 10^{-6} smaller than for permitted transitions.
- Laboratory: $F = 1$ state is depopulated by collisions; no line is seen.
- ISM: low densities, i.e., no collisions; radiative transitions possible.

Because of the ubiquity of hydrogen, 21 cm line traces gas extremely well. Self-absorption of the line is extremely unlikely $\Longrightarrow$ line visible from everywhere except for the most dense regions.

Evidence for Spiral Arms





Sketch of a typical H I emission line profile. Note: v-axis has wrong sign!

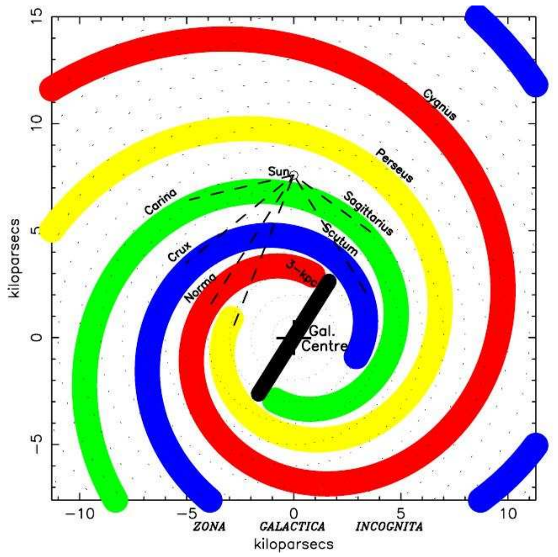
In general multiple hydrogen clouds along the line of sight. Differential rotation ⇒ Differential Doppler shift, allows to obtain $\Omega(R)$ (note: maximum v_r at $R = R_0 \sin\ell$!).

Overall: Probe of ISM structure and dynamics!

Integration over the full profile gives the column density of neutral hydrogen in this direction. Typical values: $10^{18}\,\mathrm{cm}^{-2}$ (at large gal. latitudes) to $10^{22}\,\mathrm{cm}^{-2}$ (in the gal. plane).

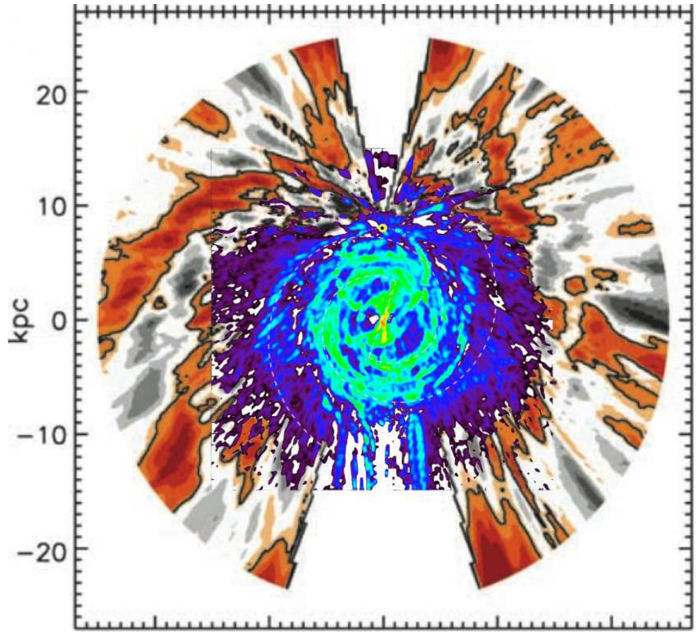
State of the art is the Leiden-Argentine-Bonn Survey (Kalberla et al., 2005).

Evidence for Spiral Arms



The spiral arm structure of Galaxy is now rather well understood

Vallee (2008)



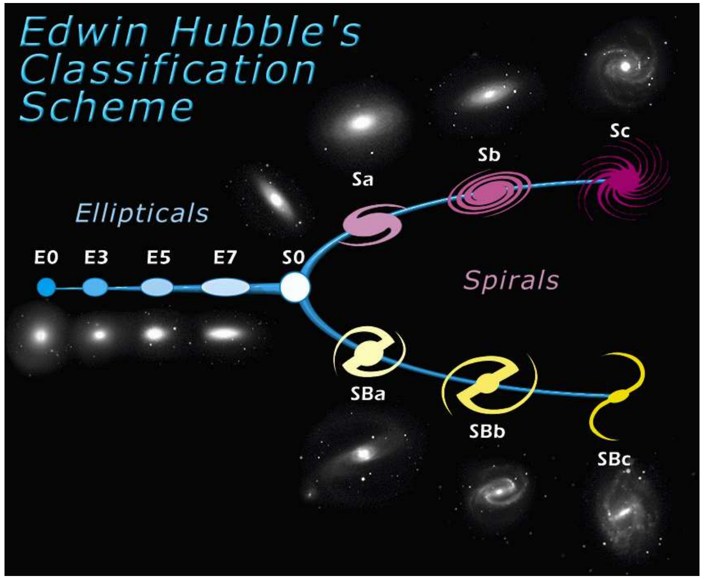
from Englmaier, Pohl, Bissanz (2008, Fig. 2; Sun is yellow dot)

Distribution of CO and H gas shows clearly the spiral structure.

Classification

1920s: Hubble and others: classification of galaxies

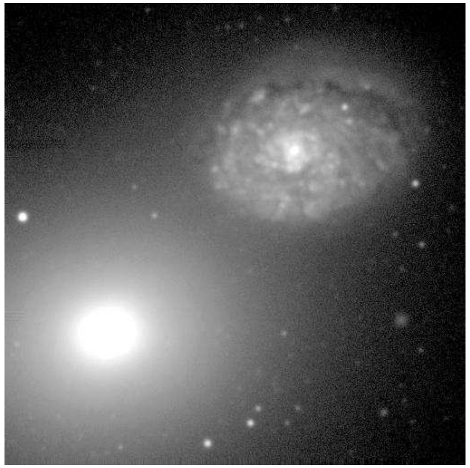
- Morphology: Appearance on photographs, photographic emulsion is blue sensitive
- *Warning:* scheme is in parts not so well defined, incomplete, and not unique
- Note: photometric (colors) and spectroscopic information are not part of the Hubble scheme.



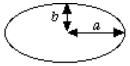
SDSS

Galaxy classification via the Hubble “tuning fork diagram”: “early types”: elliptical galaxies; “late types”: spiral galaxies, Not an evolutionary sequence!

Classification



M60 (NGC 4649), E1, U. of Alabama



Elliptical galaxies: Classification as Ex where $x = 10(a-b)/a$ (integer part; between 0 and 7)

Ellipticals are low on dust and gas, reddish color (=old stars!), typically low luminosity and low mass ($10^6\,M_\odot$)

Monsters: Also elliptical, from mergers in galaxy clusters (e.g., M87 in Virgo), M up to $10^{12}\,M_\odot$, designated cD.

Spiral Galaxies

M51 (NGC 5194 and 5195), Sc and Irr, Kitt Peak 0.9 m

Spiral Galaxies: Elliptical nucleus (“bulge”) plus disk with spiral arms, designated Sa, Sb, Sc depending on opening angle of spiral (Sa: $\sim 10^\circ$, Sc: $\sim 20^\circ$) and dominance of nucleus.

Bluer than ellipticals.

Mass content $\sim 3\times 10^{11}\,M_\odot$, with $M/L \sim 20$,

Gas content increases from Sa to Sc from 1% to 8%.

Spiral arms probably due to density wave.

Barred Spirals

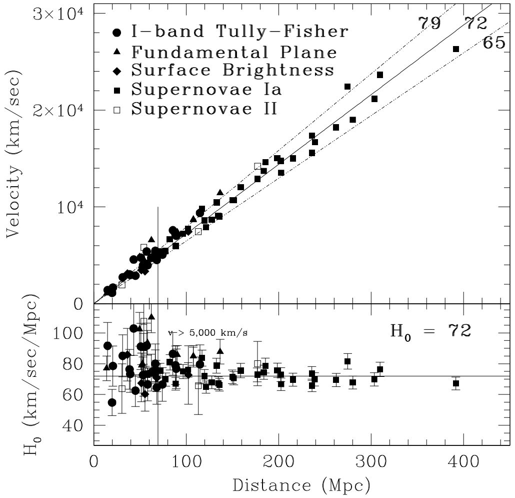
M95 (NGC 3351), SBb, INT

Barred Galaxies: Classification as SBa, SBb, SBc similar to Sx galaxies, but additional presence of a bar (cause of bar production and stability are still debated).

Similar masses and gas content as in normal spirals.

Milky Way is a barred spiral.

Expansion of the Universe



(Freedman, 2001, Fig.4)

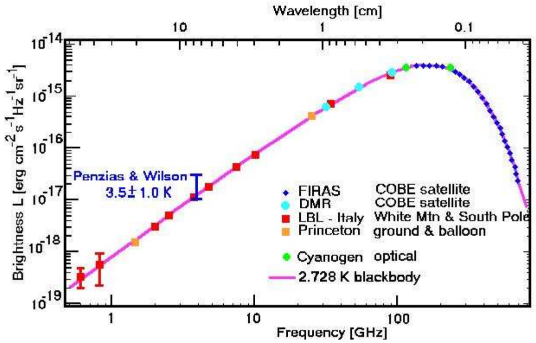
Hubble relation (1929):

The redshift of a galaxy is proportional to its distance: $v = cz = H_0 d$

where H_0: “Hubble constant”. *Measurement:* determine v from redshift (easy), d with standard candles (difficult) $\Longrightarrow H_0$ from linear regression. Hubble Space Telescope finds

$H_0 = 72 \pm 8\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$

CMB



There is a cosmic microwave background (CMB), which is a perfect black body with $T = 2.725 \pm 0.002\,\text{K}$

$\Longrightarrow$ Universe started hot, then temperature decreased as universe expanded,

$$T(z) = T_0(1+z) \tag{2.10}$$

CMB

$a(t)$	t since BB	T[K] [K]	ρ_{matter} [g cm^{-3}]	Major Events
	10^{-42}	10^{30}		Planck era, “begin of physics”
	$10^{-40\ldots-30}$	10^{25}		Inflation?
10^{-13}	$\sim 10^{-5}$ s	$\sim 10^{13}$	$\sim 10^{9}$	generation of p-p^{-}, and baryon anti-baryon pairs from radiation background
3×10^{-9}	1 min	10^{10}	0.03	generation of e^{+}-e^{-} pairs out of radiation background
10^{-9}	10 min	3×10^{9}	10^{-3}	nucleosynthesis
$10^{-4}\ldots10^{-3}$	$10^{6\ldots7}$ yr	$10^{3\ldots4}$	$10^{-21\ldots-18}$	End of radiation dominated epoch
7×10^{-4}	10^{7} yr	4000	10^{-20}	Hydrogen recombines, decoupling of matter and radiation
			Formation of structures	
1	15×10^{9} yr	3	10^{-30}	now

General structure formation

General idea of all theories of structure formation:

1. Big Bang generates initial density perturbations (=potential wells)
   density perturbations caused by Poisson statistics in the early universe, e.g., decay of inflaton or similar
2. Those density fluctuations that can grow, grow.
3. Those density fluctuations that cannot grow get smoothed out by expansion and disappear.

How fluctuations grow depends on properties of material forming structures:

Early theory (Zeldovich, 1960s): structures=baryons; large structures must form first $\Longrightarrow$ this is not what is observed.

New theory: dark matter is important:

1. DM forms initial potential wells
2. Wells develop as universe expands
3. Baryons fall into potential wells once radiation and matter decouple
4. galaxies formed first, clusters still forming

Dark Matter

Detailed theory of structure formation uses numerical simulations, using CMB boundary conditions and assumptions on dark matter:

Hot Dark Matter: relativistic particles (e.g., neutrinos): moving with $v \sim c$. Fast particles

$\Longrightarrow$ smears out small density perturbations

$\Longrightarrow$ “top down structure formation”

Not what is observed

(observed: galaxies were there first, clusters are still forming)

Cold Dark Matter: slow particles, condense first, forming potential wells while baryonic matter is still coupled to radiation.

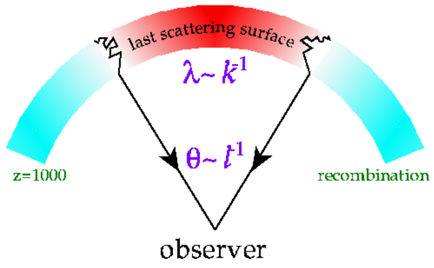
Once radiation decouples from matter (when universe is cold enough), matter falls in gravity wells.

$\Longrightarrow$ “bottom up structure formation”

Closer to what is observed

Luminous baryonic mass traces Dark Matter

Dark Matter



courtesy Wayne Hu

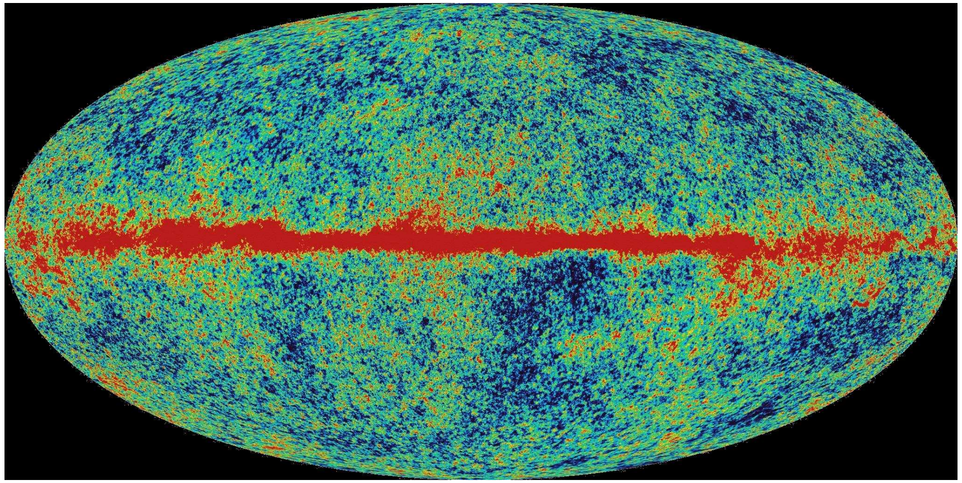
After BB: Universe is dense ("forry"), photons scatter efficiently off electrons $\Longrightarrow$ coupling of matter and radiation

Universe cools: recombination of protons and electrons to form hydrogen
$\Longrightarrow$ no free electrons
$\Longrightarrow$ no scattering
$\Longrightarrow$ photons stream freelty

Photons leaving overdense regions loose energy (gravitational red shift)

$\Longrightarrow$ visible as a temperature fluctuation (Sachs-Wolfe-Effect)

Leads to CMB fluctuations $\sim$ gravitational potential at $z \sim 1100$ (380000 yr after big bang) $\Longrightarrow$ structure



WMAP, W-Band, $\lambda = 3.2\,\mathrm{mm}$, $\nu = 93.5\,\mathrm{GHz}$, resolution 0.21°